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Grassroots Design of Heat Exchanger Networks of Crude Distillation Unit

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Due to the increase of economic competition, many refineries have tried to reduce production cost in order to achieve higher rate of return. One way to improve energy efficiency of the refinery having crude distillation units, high-energy-consuming units, is recovering heat from hot product streams to preheat cold stream of crude by complex heat exchanger networks (HENs). These HENs help reduce energy consumption at crude furnaces and product coolers. They can be designed by optimization model or stage model by Yee and Grossman (1990). The results of grassroots network design are shown at different exchanger minimum temperature approaches (EMAT) between hot and cold streams of 30°C, 25°C, 20°C, 15°C, and 10°C, which can save the energy of furnaces and coolers to 15 %, 20%, 23%, 25%, and 29%, respectively, compared to the existing one.

1. Introduction

Due to the increase of economic competition and environmental awareness movements, many leading firms have tried to reduce production cost in order to achieve a higher rate of return. This principle has been applied to many petroleum refinery businesses; oil price has been increasing and the market has been extremely competitive. Because of the current situation the efficient ways are demanded to improve the energy efficiency of the plant. The crude distillation unit (CDU) is one of the largest energy-consuming units in the refinery, having a complex heat exchanger network transferring heat from hot product streams to the crude oil feed. By preheating the crude, this HENs reduces fuel consumption in the crude furnace. Many technological developments in the oil refineries also drives applied technology to improve CDU and HENs energy performance, combined with the mathematical programming model for example, Linear Programming (LP), Non-Linear Programming (NLP), Mixed Integer Linear Programming (MILP), and Mixed Integer Non-Linear Programming (MINLP). For this research, optimization model or stage model by Yee and Grossman (1990) are applied to do the grassroots design of heat exchanger networks. The results of grassroots

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network design are shown at different EMAT with the energy consumption of furnaces and coolers.

2. Stage model

The stage model is based on the stage-wise superstructure representation proposed by Yee et al. (1990) . The structure is shown in Figure 1. Within each stage of superstructure, possible exchanger between any pair of hot and cold streams can occur. Heater and coolers are placed at the end of cold and hot streams, respectively.The objective finction of the model is to minimize the duty of heater, cooler and number of exchangers under the constraint functions of energy balance, thermodynamics, and logical constraints.

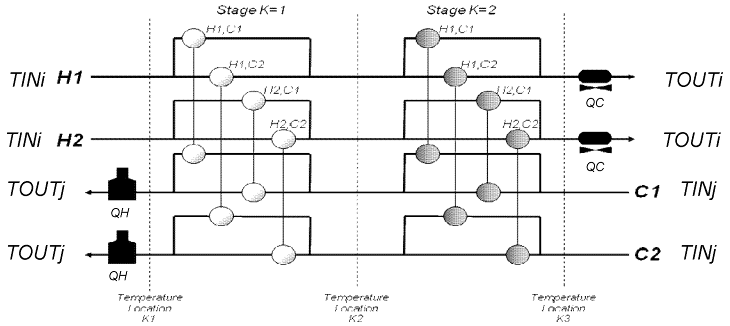

Figure 1. *Two-stage model structure*

The target temperatures and flow rate of hot and cold process streams are fixed and the stage-model will design HEN into two stages (K1 and K2) with the minimum utility usages and number of exchangers for fixed EMAT value. The constraints and objective function of stage model are shown below.

Overall heat balance for each stream.

$$(TIN_i - TOUT_i)F_i = \sum_{k \in ST} \sum_{j \in CP} q_{ijk} + qcu_i \qquad i \in HP$$

$$(TOUT_j - TINj)F_j = \sum_{k \in ST} \sum_{i \in HP} q_{ijk} + qhu_j \qquad j \in CP$$

Heat balance at each stage.

$$(t_{i,k} - t_{i,k+1})Fi = \sum_{j \in CP} q_{ijk} \qquad k \in ST, i \in HP$$

$$(t_{j,k} - t_{j,k+1})Fj = \sum_{i \in CP} q_{ijk} \qquad k \in ST, j \in HP$$

Assignment of superstructure inlet temperatures.

$$TIN_i = t_{i,1}$$

$$TIN_j = t_{j, NOK+1}$$

Feasibility of temperatures.

$$t_{i,k} \le t_{i,k+1} \qquad k \in ST, i \in HP$$

$$t_{j,k} \le t_{j,k+1} \qquad k \in ST, j \in CP$$

$$TOUT_i \le t_{i,NOK+1} \qquad i \in HP$$

$$TOUT_j \le t_{j,1} \qquad j \in CP$$

Hot and cold utility load.

$$(t_{i,NOK+1} - TOUT_i)\, Fi = qcu_i \qquad i \in HP$$

$$(TOUT_j - t_{i,1})\, F_j = qhu_j \qquad j \in CP$$

Logical constraints.

$$q_{ijk} - \Omega\, z_{ijk} \leq 0 \qquad i \in HP,\ j \in CP\ ,\ k \in ST$$

$$qcu_i - \Omega\, zcu_i \leq 0 \qquad i \in HP$$

$$qhu_j - \Omega\, zhu_j \leq 0 \qquad i \in CP$$

$$z_{ijk},\ z_{cui},\ zhu_j = 0,1$$

Calculation of approach temperatures.

$$\mathrm{d}t_{ijk} \leq t_{i,k} - t_{j,k} + \Gamma(1 - \mathrm{z}_{\mathrm{ijk}}) \qquad k \in ST,\ i \in HP,\ j \in CP$$

$$\mathrm{d}t_{ijk+1} \leq t_{i,k+1} - t_{j,k+1} + \Gamma(1 - \mathrm{z}_{\mathrm{ijk}}) \qquad k \in ST,\ i \in HP,\ j \in CP$$

$$\mathrm{d}tcu_i \leq t_{i,NOK+1} - TOUT_{CU} + \Gamma(1 - \mathrm{zcu}_{\mathrm{i}}) \qquad i \in HP$$

$$\mathrm{d}thu_i \leq TOUT_{HU} - t_{j,1} + \Gamma(1 - \mathrm{zhu}_{\mathrm{j}}) \qquad j \in CP$$

The temperature between the hot and cold streams at any point of any exchanger will be at least EMAT:

$$\mathrm{d}t_{ijk} \leq \mathbf{EMAT}$$

Objective function. The objective function is to minimize utility cost and capital cost

$$\mathbf{Min} \ \sum_{i \in HP} CCU\, qcu_i + \sum_{j \in CP} CHU\, qhu_j + \sum_{i \in HP} \sum_{j \in CP} \sum_{k \in ST} CF_{ij} z_{ijk} + \sum_{i \in HP} CF_{i,CU}\, zcu_{ijk} + \sum_{j \in CP} CF_{j,HU}\, zhu_j$$

3. Metodology

The grassroots design of HENs using the data from the refinery is generated following below steps.

3.1 Simulation of the existing process:

The step is to generate the process condition in CDU by commercial simulation software.

3.2 Stage model configuration:

The stage model is configurated by mathematical programming. The objective function was to minimize process duties at heater, cooler and number of exchanger. The variables were the possible match between hot and cold streams in each stage, the EMAT was varied to find the alternative design of HENs. The EMAT was adjusted to 30°C, 25°C, 20°C, 15°C, and 10°C, resspectivly.

3.3 Flowsheet simplification:

This step is to simplify the existing process flow diagram for doing the grid diagram consisting of hot and cold stream with exchangers. And the process streams will be used for stage model to generate the grassroots design of HENs.

3.4 HEN design verification:

The grassroots design of HEN from the stage model will be verified by the process simulation sorftware.

4. Result and Dicussion

The result of this work were reported in the simplified flowsheet and compared with the existing HENs.

4.1 Simulation of the existing process:

For the simulation program the actual condition data was used as the input data to simulate the existing unit (Figur 2.). The result shows total duties at furnace and coolers were 105.2 MWatt and 100.8 MWatt, respectively.

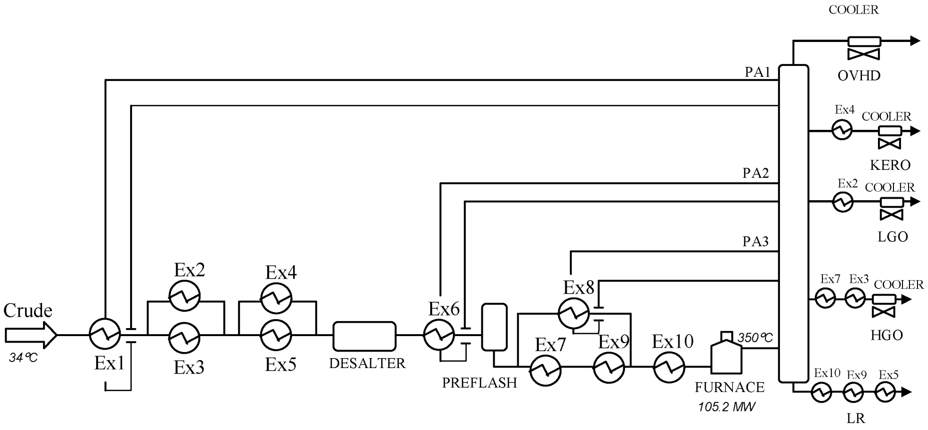

Figure 2. Existing HEN

4.2 Stage model configuration:

The results of the stage model at EMAT = 30°C, 25°C, 20°C, 15°C, and 10°C, are the grassroots design of HENs which can reduce the duties of furnace(QH) and coolers(QC) as shown in Table 1.

Table1. The result of grassroots design

Design	EMAT (°C)	Number of process exchanger	Utilities (MWatt)			
			QH	Saving (%)	QC	Saving (%)
Base case	35	10	105.2	0	100.8	0
Alternative design 1	10	10	79.4	25	66.5	34
Alternative design 2	15	10	83.2	21	70.3	30
Alternative design 3	20	10	85.6	19	72.7	28
Alternative design 4	25	10	89.2	15	76.3	24
Alternative design 5	30	11	94.2	10	81.4	19

4.3 The grassroots design of HENs:

To compare the structure of grassroots design of HEN with the existing one, they are shown in Figures 3- 8.

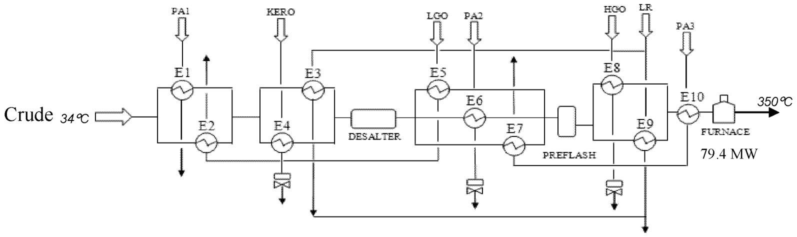

Figure 3. Alternative design 1 with EMAT = 10 ºC

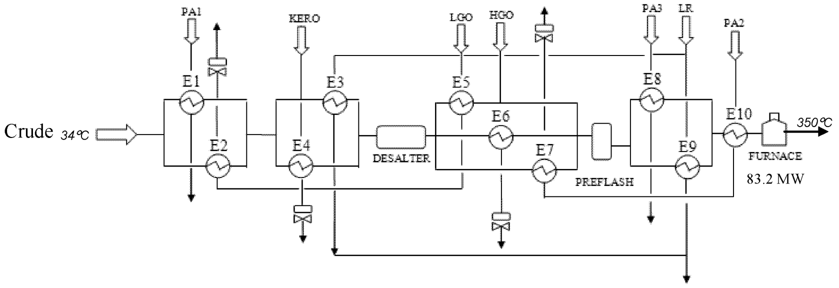

Figure 4. *Alternative design 2 with EMAT = 15 ºC*

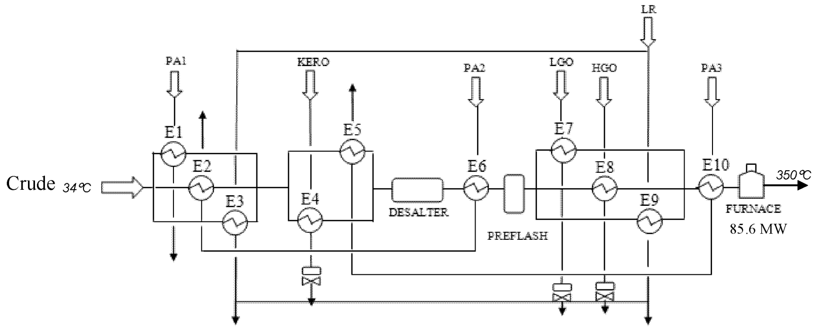

Figure 5. *Alternative design 3 with EMAT = 20 ºC*

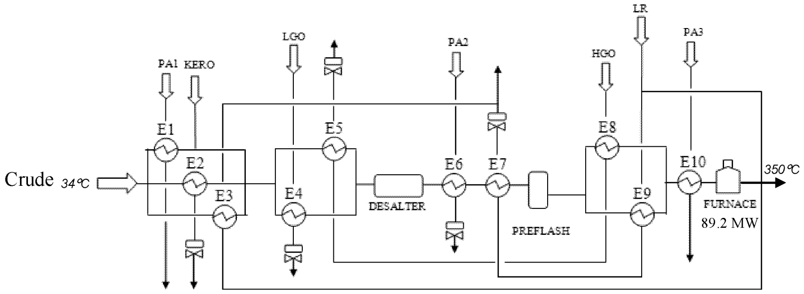

Figure 6. *Alternative design 4 with EMAT = 25 ºC*

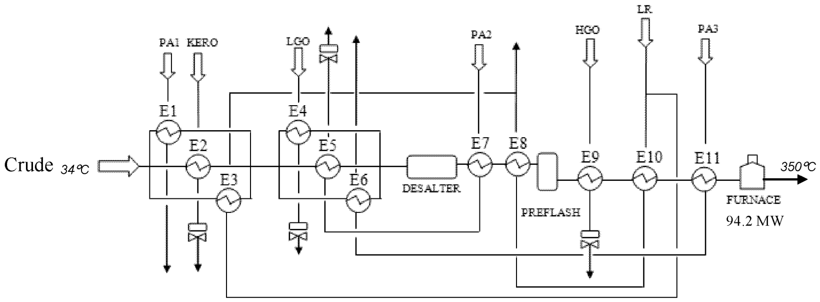

Figure 7. *Alternative design 5 with EMAT = 15 ºC*

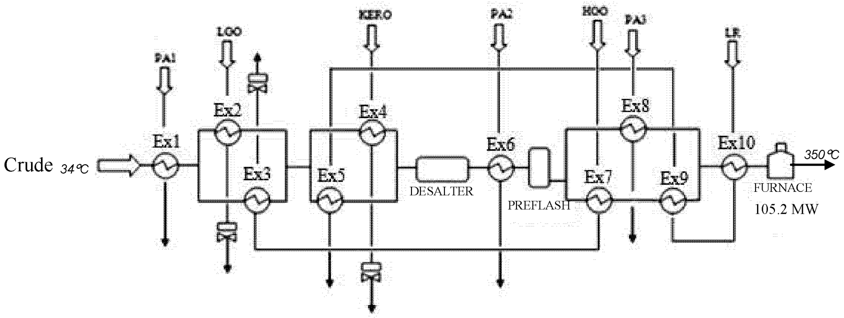

Figure 8. *Existing design with EMAT = 35 ºC*

5. Conclusions

The results of grassroots network design were concluded at different EMAT of 30°C, 25°C, 20°C, 15°C, and 10°C, which can save the energy usage of furnaces and coolers to 15 %, 20%, 23%, 25%, and 29%, respectively.

Nomenclature

HP = Set of Hot Process Streams
CP = Set of Cold Process Streams
ST = Set of Stage No.
TIN = inlet temperature of stream
CCU = unit cost for cold utility
β = exponent for area cost
Ω = upper bound for heat exchange

F = heat capacity flow rate
U = overall heat transfer coefficient
CF = fixed charge for exchangers
TOUT= outlet temperature of stream
CHU = unit cost of hot utility
NOK = total number of stages
Γ = upper bound for temperature difference

dt_{ijk} = temperature approach for match (i,j) at temperature location k
$dtcu_i$ = temperature approach for match of hot stream i and cold utility
$dthu_j$ = temperature approach for match of cold stream j and hot utility
q_{ijk} = heat exchanged between hot process stream i and cold process stream j in stage k
qcu_i = heat exchanged between hot stream i and cold utility
qhu_j = heat exchanged between hot stream and cold stream j
$t_{i,k}$ = temperature of hot stream i at hot end of stage k
$t_{j,k}$ = temperature of cold stream j at hot end of stage k
z_{ijk} = binary variable to denote existence of match (i,j) in stage k
z_{cui} = binary variable to denote that cold utility exchanges heat with stream i
z_{huj} = binary variable to denote that hot utility exchanges heat with stream j

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